

# On the Formation of Galaxy Halos: Comparing NGC 5128 and the Local Group Members

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## ABSTRACT

The metallicity distribution function (MDF) for the old red-giant stars in the halo of NGC 5128, the nearest giant elliptical galaxy, is virtually identical with the MDF for the old-disk stars in the LMC and also strongly resembles the halo MDF in M31. These galaxies all have high mean halo metallicities ( $\langle m/H \rangle \simeq -0.4$ ) with very small proportions of low-metallicity stars. These observations reinforce the view that metal-rich halos are quite normal for large galaxies of all types. Such systems are unlikely to have built up by accretion of pre-existing, gas-free small satellite galaxies, unless these satellites had an extremely shallow mass distribution ( $\Delta \log N / \Delta \log M \gtrsim -1$ ). We suggest that the halo of NGC 5128 is more likely to have assembled from hierarchical merging of gas-rich lumps in which the bulk of star formation took place during or after the merger stage.

*Subject headings:* galaxies: halos — galaxies: individual (LMC, NGC 5128) — galaxies: stellar content — galaxies: formation

## 1. Introduction

Part of the early historical record of galaxy formation is left behind in the ages and metallicities of the old stellar populations. Much recent effort has gone into empirically deducing the star formation history and the age-metallicity relations (AMR) within the Local Group galaxies (see, e.g., Mateo 1998, for an extensive review). For progressively more distant systems, however, only the more luminous parts of the color-magnitude diagram can be observed, and deriving an accurate AMR becomes increasingly difficult. Large ellipticals present a special challenge because none are close enough to the Local Group to allow direct, comprehensive probes into their stellar populations.

Recently, we have used deep ( $V, I$ ) photometry from *HST*/*WFPC2* to obtain color-magnitude diagrams for fields in the halo of the nearest giant E galaxy, NGC 5128 (Harris et al. 1999; Harris & Harris 2000, hereafter Papers I and II; see also Marleau et al. 2000 for *NICMOS* near-infrared data to similar photometric limits). Our two target fields are at projected distances of 21 and 31 kpc from the galaxy center and thus represent its remote halo, far from the more metal-rich inner bulge and most recent star formation activity (see Paper I). These CMDs reveal the top  $\sim 2.5$  magnitudes of the old-halo red-giant branch (RGB). The RGB stars by themselves cannot be used to construct a true age-metallicity relation, but because the RGB loci for old stars are far more sensitive to metallicity than age, we can use them to construct a first-order *metallicity distribution function* (MDF) for the NGC 5128 halo – the first such one for any giant elliptical and one which does not rely on indirect arguments from luminosity-weighted integrated light. The MDF is an important step towards an eventual complete AMR.

Our knowledge of MDFs for the various Local Group galaxies has also increased dramatically in quality over the past few years, and it is natural to ask which of these “template” MDFs (if any) might resemble the halo of the giant elliptical. Giant E galaxies are expected to have formed through a wide range of possible routes including hierarchical merging of gas clouds at early times, later merging of disk galaxies, and ongoing accretion of small satellites. Many of these candidate pre-galactic units (from small gas clouds to fully formed large disk galaxies) should resemble the dwarfs and disk galaxies found in the Local Group.

## 2. Comparisons of Metallicity Distributions

The outer halo of NGC 5128 has an MDF which peaks at  $[m/H] \simeq -0.45$  and, although a low-metallicity “tail” is present, the number of stars with  $[m/H] < -1$  is remarkably small. (By contrast, the halo of the Milky Way is populated almost entirely by stars with  $[m/H] < -1$ .) In Paper II, we noted that the overall shape of the NGC 5128 MDF is roughly similar to those of the compact dwarf elliptical M32 (Grillmair et al. 1996) and the halo of M31 (Durrell et al. 2001; Rich et al. 2001). Perhaps surprisingly, however, it bears an even closer resemblance to the MDF drawn from the old stars in the Large Magellanic Cloud.

A direct comparison between NGC 5128 and the LMC is displayed in the upper panel of Figure 1. For NGC 5128, we show the MDF defined by the 436 halo RGB stars in our database brighter than  $M_I = -3.0$ , i.e. the stars in the brightest one magnitude of the giant branch where the RGB color range (and metallicity sensitivity) is largest and the spread due to photometric measurement uncertainty is negligible (see Paper II). For the LMC, we use the “outer disk” sample from Cole et al. (2000a), which includes 39 RGB stars with high-quality spectroscopic abundances from the age-insensitive Ca II index. MDFs for the LMC old disk derived through Strömgren photometric indices are also available for samples of many hundreds of stars (see Cole et al. 2000a; Larsen et al. 2000; Dirsch et al. 2000, for comprehensive discussions) and these agree closely with the spectroscopically based distributions.

Two additional MDFs drawn from the Milky Way and M31 are shown in the lower panel of Figure 1. The halo of M31 (Durrell et al. 2001) has an MDF with the same peak as NGC 5128 or the LMC, though with a more prominent low-metallicity tail. The small members of the Local Group, from the SMC downward, have lower mean abundances by at least a factor of two, as do the halos of M33 and the Milky Way itself (Ryan & Norris 1991; Pappas et al. 2000). Both the old disk and bulge of the Milky Way (Wyse & Gilmore 1995; McWilliam & Rich 1994; Frogel et al. 1999) are two to three times more metal-rich than the NGC 5128 halo. Finally, the compact elliptical M32, at least in the inner regions studied by Grillmair et al. (1996), also has a high mean metallicity similar to the bulges of the large spirals.

Statistical comparisons of the NGC 5128 halo with M31 and the LMC show that (a) the LMC old disk differs from NGC 5128 at only the  $\sim 45\%$  confidence level (i.e., the two are indistinguishable); and (b) the M31 halo is marginally different (95% confidence), primarily because of its more prominent low-metallicity tail. It should be noted that all of these MDFs are tied to the same Milky Way globular cluster metallicity scale through RGB model tracks and the fiducial loci of well studied clusters (see the discussions of Paper II and Cole et al.). Formal statistical comparisons aside, we suggest that the MDFs of the oldest stars in these three galaxies are, for all practical purposes, quite similar despite their wide variety of host galaxy type.

This combined evidence suggests that the halo of NGC 5128 is not a relic of mergers of either large Milky-Way-like disks or bulges (which are distinctly too metal-rich), or dwarf stellar systems (which are too metal-poor). By contrast, if many intermediate-sized objects like the LMC were merged and their light allowed to age-fade for several Gyr, the result would be very like what we now see in the NGC 5128 halo. In the next section we will discuss the range of possibilities a bit further.

### 3. Discussion: Accretion or Merger?

One view of large-galaxy formation, explored in detail by Côté et al. (2000), is that galaxy halos built up by simple accretion of smaller objects which had already formed their own stars and thus held little or no remaining gas when they merged. Under this assumption, the MDF of the final halo is the straightforward result of combining the mass distribution of the accreted satellites with their metallicity distribution versus mass (or luminosity).

The empirical trend of mean metallicity  $[m/H]$  with luminosity  $M_V^T$  for Local Group members is shown in Figure 2. For all objects in Fig. 2, the metallicities are averages of large samples of individual stars. The data are taken from Mateo (1998), with various more recent measurements for Cetus (Whiting et al. 1999), M32 (Grillmair et al. 1996), the Andromeda dwarf spheroidals (Da Costa et al. 2000; Côté et al. 1999; Armandroff et al. 1998, 1999; Grebel & Guhathakurta 1999), the SMC (Larsen et al. 2000), Fornax (Saviane et al. 2000), Sagittarius (Bellazzini et al. 1999; Layden & Sarajedini 2000), and M33 (Pappas et al. 2000). For the three large spirals, the

metallicity refers to the halo and, for the SMC and LMC, it refers to the outer old-disk population. The galaxy luminosities are taken from the Local Group catalog of van den Bergh (2000). There is significant scatter, but the overall trend displayed by the dwarfs plausibly follows the scaling relation  $Z \sim L^{0.37}$  predicted by Dekel & Silk (1986). Figure 2 reinforces the view that for large galaxies of all types, moderately metal-rich halos may well be the norm, not the exception.

To explore the accretion model a bit more quantitatively, we employ a modified version of the numerical method of Côté et al. (2000). The relative numbers of accreted satellites are assumed to follow a power-law distribution  $dN/dL \sim L^\alpha$ . The lower limit  $L_{min}$  of the distribution is set at  $M_V^T = -8.5$ , similar to the smallest dwarf spheroidals (Draco, Ursa Minor), and the upper limit  $L_{max}$  at  $M_V^T = -19.5$ , which is equivalent to about  $2 \times 10^{10} M_\odot$  assuming  $(M/L)_V = 4$ , or about four times the mass of the LMC (which is  $\simeq 5 \times 10^9 M_\odot$ ; Alves & Nelson 2000). The upper mass cutoff by definition sets the maximum metallicity that can be contributed by the accreted halo stars. Its value is a somewhat arbitrary choice, but in setting it roughly at this point we are guided by recent simulations of the mass spectra of pregalactic clouds in standard cold-dark-matter cosmologies, which typically give  $\alpha \simeq -1.8 \pm 0.2$  and upper ends  $\sim 10^{10} M_\odot$  (e.g., Frenk et al. 1996; Weil & Pudritz 2001).

Next, the MDF within each accreted dwarf is assumed to have a Gaussian form<sup>1</sup> with dispersion  $\sigma[\text{m}/\text{H}] = 0.35$  (see Côté et al. regarding the empirical evidence for a uniform  $\sigma$ ) and with mean  $\langle \text{m}/\text{H} \rangle$  given by the correlation in Fig. 2, namely  $\langle \text{m}/\text{H} \rangle = -3.33 - 0.148 M_V^T$ . We select galaxies in equal luminosity intervals, in proportional numbers given by the adopted power law, and then add them together to calculate the combined MDF. Our simulation is not intended to match the much more extensive range of Monte Carlo realizations explored by Côté et al., but only to delineate changes to the first-order features of the MDF as the slope parameter  $\alpha$  is varied.

In Figure 3 we show the results for model halos built from four different input mass distributions ( $\alpha = -2.0, -1.8, -1.0, 0.0$ ). For the steepest mass spectra (largest negative  $\alpha$  values), the summed MDFs are very broad and dominated by the large numbers of metal-poor dwarfs, though the detailed shape is quite sensitive to  $\alpha$ . Nevertheless, for any  $\alpha \lesssim -1$  the model predicts too many low-metallicity stars to successfully match NGC 5128.

With suitable combinations of  $\alpha$  and  $L_{max}$  it is possible to obtain approximate matches to a wide variety of actual MDFs. However, for distributions as narrow and as metal-rich as we find in NGC 5128, the range of solutions is pushed strongly towards both a high  $L_{max}$  (LMC-like or

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<sup>1</sup>Ideally, we might expect the MDF for each individual dwarf to follow the Simple Model (closed-box enrichment) of chemical evolution (see Côté et al.), since in this case each satellite is assumed to have completed its star formation in isolation. However, in reality many dwarf galaxies have much smaller relative numbers of low-metallicity stars than the Simple Model predicts, and their observed MDFs more nearly approximate a symmetric Gaussian distribution (see Paper II for additional examples). A notable exception to this trend is the halo of M31, in which the MDF has the prominent low-metallicity ‘tail’ that rather accurately mimics a closed-box model with effective yield  $y_e = 0.005$  (Durrell et al. 2001).

larger) and a shallow mass spectrum  $\alpha$ . For  $\alpha > -1$ , the model result becomes much less sensitive to  $\alpha$  because the summed MDF is dominated by the few largest satellites. These flat input spectra can yield MDFs with approximately the right mean and dispersion to describe NGC 5128 and the other galaxies mentioned above. That is, under the accretion scenario, NGC 5128 would likely have assembled almost entirely from rather large satellites, similar to the LMC, SMC, or M32 in size.

Mass distributions with  $\alpha > -1$  are not out of the question on observational grounds, but are certainly unusual. Field galaxies and small groups typically show  $\alpha = -1.0$  to  $-1.3$  in the dwarf regime (e.g., Binggeli et al. 1988; Jerjen et al. 2000; Zabludoff & Mulchaey 2000; Loveday 2000; Blanton et al. 2001). Notably, the slope for the Centaurus cluster itself, within which NGC 5128 is the central dominant member, is near  $\alpha \sim -1.3$  (Jerjen et al. 2000), too steep for the purposes of the accretion model. In bigger clusters of galaxies,  $\alpha$ -values in the range  $-1.5 \pm 0.2$  are frequently quoted, though the results appear to depend on limiting magnitude as well as environment (Ferguson & Sandage 1991; de Propris & Pritchet 1998; Secker et al. 1997, among others). Slopes as high as  $\sim -1.7$  to  $-2$  have been found for environments within rich clusters and for the faintest part of the dwarf sequence (e.g., Smith et al. 1997; Trentham 1997, 1998; Phillipps et al. 1998; de Propris et al. 1995). *If* these present-day slopes are fair indicators of the mass spectra at early times, then most of them would produce accreted halos with intermediate metallicity and a broad internal range, but not as high a mean as in M31 or NGC 5128.

Constraints on the choice of  $(L_{max}, \alpha)$  are driven by the dispersion in the observed MDF as well as its mean. For example, we could produce a model MDF with a steep  $\alpha \lesssim -1.5$  and with the same *mean* metallicity as in NGC 5128 or M31, if we also increased  $L_{max}$  beyond the value adopted above. But this combination would bring in too many stars at high metallicity (from the very most massive accreted satellites) *and* too many stars at low metallicity (from the large numbers of small satellites), increasing the MDF dispersion beyond acceptable bounds. Within the context of the accretion model as given, we suggest that values of  $L_{max}$  corresponding to masses  $\lesssim 5 \times 10^9 M_\odot$  or  $\gtrsim 5 \times 10^{10} M_\odot$  would not fit the NGC 5128 or M31 halo MDFs for any plausible slope  $\alpha$ . That is,  $L_{max}$  needs to be at least as high as the LMC itself in order to supply enough high-metallicity stars (after which  $\alpha$  can be adjusted to match the low-metallicity end correctly); but if  $L_{max}$  is *many* times larger than the LMC, i.e. approaching the Milky Way bulge in size, then too many very high-metallicity stars are brought in and no  $\alpha$ -slope can compensate for it.

An alternate modelling approach is to assume that the pregalactic lumps still had a large fraction of gas at the time when they were beginning to merge. This route opens up much more parameter space for formation models, including such processes as the rates of star formation within each dwarf, the merger rate, or interactions through winds and feedback (e.g., Cole et al. 2000b; Kauffmann et al. 1993; Frenk et al. 1996; Scannapieco & Broadhurst 2001). Such models provide several possibilities for reconciling a steep initial mass spectrum of pregalactic fragments ( $\alpha \sim -2$ ) with a final MDF that has moderately high mean metallicity and almost no low-metallicity stars. It is not yet clear which of these approaches would apply best in detail to NGC 5128. A qualitative but self-consistent picture for its formation would be that NGC 5128 built up from a moderately

flat mass spectrum of subsystems (consistent with its local observed  $\alpha$ -level), and that these had already formed some stars of their own but were still mostly gaseous. The major stage of star formation then took place within the much larger potential well of the new giant elliptical, which could hold on to most of the gas and complete the conversion into stars. As we discuss in Papers I and II, this basic scenario has the extra advantage that it is also consistent with the characteristics of the globular cluster system in NGC 5128.

The halo of the Milky Way itself (along with the less luminous spiral M33) is strikingly different from the other large galaxies in Fig. 2. Côté et al. show in detail that the very low mean metallicity  $\langle m/H \rangle = -1.6$  which characterizes both these spirals might plausibly have built up from accretion of stellar subsystems obeying an input mass distribution  $\alpha \sim -1.8$  to  $-2.0$ . However, the observed slope of the luminosity function for the Local Group dwarfs is  $\alpha \simeq -1.1$  (Pritchett & van den Bergh 1999), very much at odds with this requirement.<sup>2</sup> The recent discovery of the Sagittarius dwarf now being tidally disrupted within the Galactic halo has been seized on as the “smoking gun” evidence that much or most of the Milky Way halo may have been accreted, but clearly it is an atypical event. At  $\langle m/H \rangle = -1.2$  and  $M_V^T = -13.8$  (Bellazzini et al. 1999; Layden & Sarajedini 2000), Sagittarius is considerably more massive and metal-rich than the average satellites could have been.

More generally, *if* the halos of M31 and the Milky Way were built by stellar accretion, this would have required strong and apparently arbitrary differences in the type of satellite accreted. For M33, less can be said in detail since the available data are still preliminary (Pappas et al. 2000). However, it is intriguing that although M33 resembles the LMC in total size and the general age distribution of its stellar population, its sparse and metal-poor halo appears to more closely resemble that of the much bigger Milky Way.

The Milky Way’s extremely metal-poor halo is, in a sense, the least likely result for a big galaxy assembled by hierarchical merging. If it was built from pure accretion, it would have required the extreme combination of a steep input mass spectrum and fragments which were completely stellar. If instead it was built from hierarchical merging of gaseous fragments, it would have required gas clouds which merged into the Galactic halo but then left almost all their original gas unused, allowing the majority of their gas to dissipate and fall inward to the bulge before it could form stars (e.g., Ibata & Gilmore 1995; Samland et al. 1997; Chiappini et al. 2001).

The discrepancy between the theoretically expected *mass* spectrum slope ( $\alpha \sim -1.8$ ) and the much shallower values in the *luminosity* distribution now observed in environments like Centaurus and the Local Group ( $\alpha \sim -1.2$ ) is also a concern. The present-day observed spectrum may, of course, not be as steep as the original pregalactic one, perhaps because the stellar content of the

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<sup>2</sup>A slope this shallow would, however, be much closer to matching the metal-rich halo of M31. See Ibata et al. (2001) for new evidence that M31 may have tidally stripped large numbers of stars from M32 and NGC 205, which are moderately metal-rich. The dichotomy between the Milky Way and M31 halos is one of the strongest anomalies in the Local Group.

smallest ones dissipated entirely, leaving them as only dark halos (e.g., Klypin et al. 1999). Thus a number of interpretive problems remain for future study.

#### 4. Summary

Metallicity distribution functions based on large samples of star-by-star measurements are now available for several large galaxies, as well as many dwarfs in the Local Group and elsewhere. This material shows that the MDFs for the oldest stars in NGC 5128, M31, and the LMC are metal-rich and closely similar to one another despite their very different environments. With the aid of simple numerical simulations, we argue that the halo populations in these big galaxies are unlikely to have formed exclusively by direct accretion of smaller stellar systems, *unless* these small satellites had a unrealistically flat input mass distribution  $\alpha > -1$  or (in an even more extreme view) were all LMC-like in size.

Hierarchical merging of gas-rich fragments would allow a much wider range of possibilities for MDFs in these large galaxies and make it easier to produce moderately metal-rich systems. The fact that the MDFs in the large galaxies discussed above are so similar to one another leads us to speculate that their early histories may have resembled one another in ways not yet fully understood.

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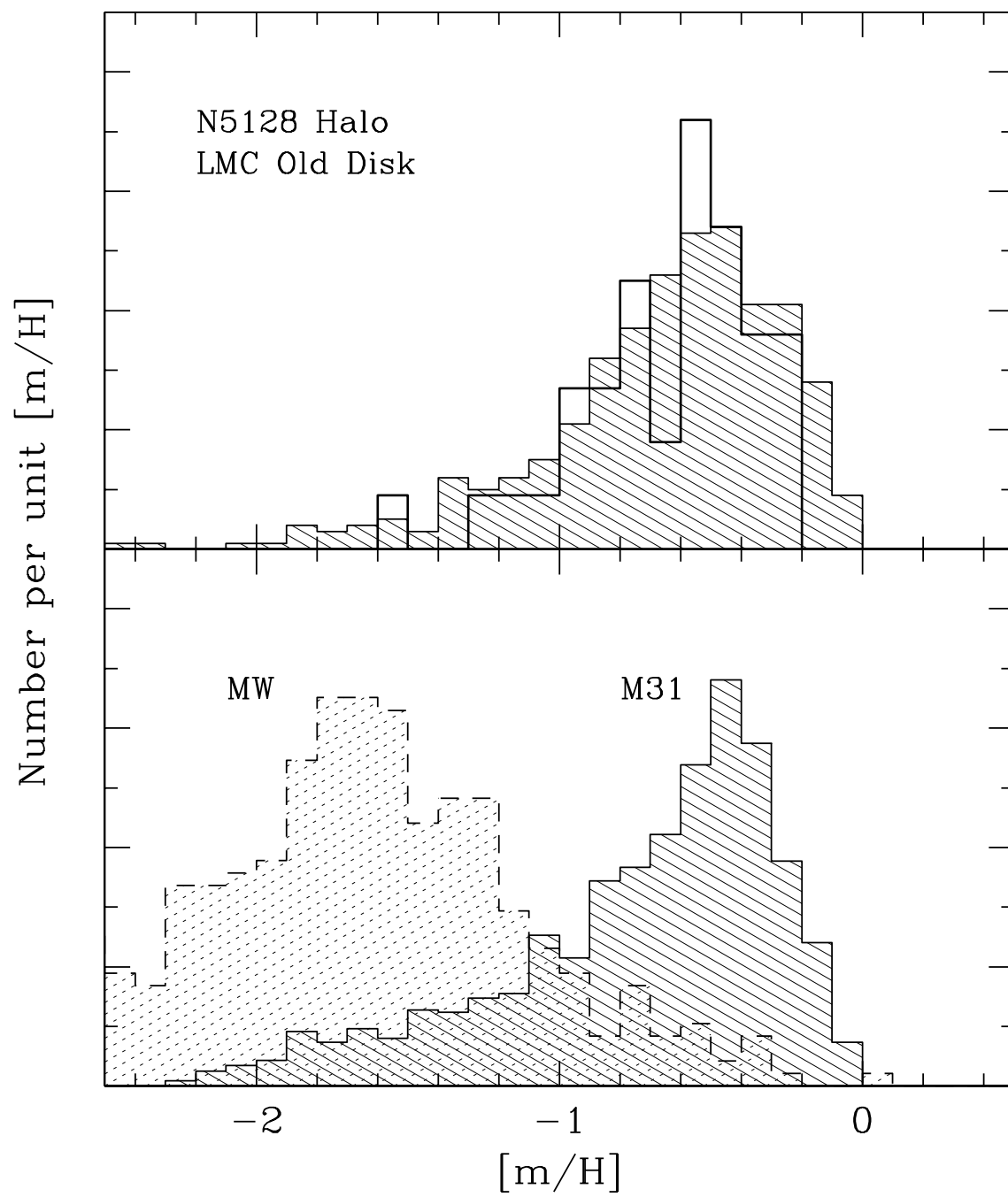


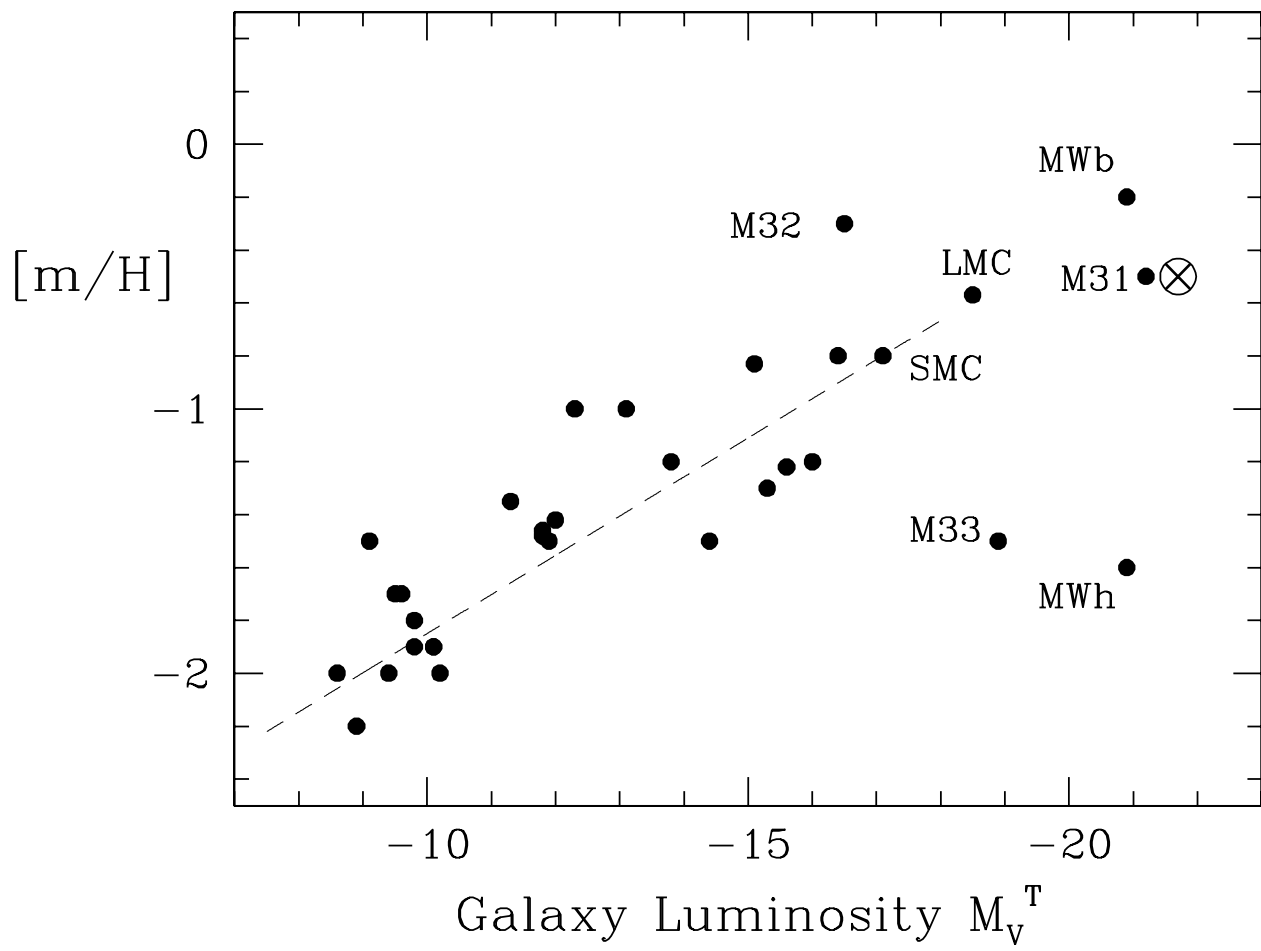
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Fig. 1.— *Upper panel:* Metallicity distribution functions for the stars in the outer halo of the giant elliptical NGC 5128 (shaded histogram) and red-giant stars in the outer disk of the Large Magellanic Cloud (heavy solid line). The two distributions are statistically identical. *Lower panel:* Metallicity distributions for stars in the halo of M31 (shaded histogram at right), and the halo of the Milky Way (stippled histogram at left).

Fig. 2.— Mean metallicity of stars in Local Group galaxies (*solid dots*) plotted against galaxy luminosity  $M_V^T$ . The *circled cross* denotes the halo of NGC 5128. For NGC 5128, M31, LMC, SMC, and M33 the points refer to the old-halo stars only. The Milky Way is plotted twice, separately for its halo (MWh) and bulge (MWb). The expected scaling relation for dwarf galaxies formed in CDM potential wells,  $Z \sim L^{0.37}$  (Dekel & Silk 1986; Côté et al. 2000), is shown as the dashed line.

Fig. 3.— Metallicity distribution function for the NGC 5128 halo (shaded histogram) and for various simulated MDF models as described in the text. The halo is assumed to be built up from the sum of accreted satellites following a mass distribution function  $dN/dM \sim M^\alpha$ . Four illustrative models show the average MDFs for  $\alpha = -2.0$  (leftmost solid line),  $-1.8$  (middle dashed line),  $-1.0$  (rightmost solid line), and  $0.0$  (rightmost dashed line).





Number of Stars

